22 JUNE 2022

EEMS098

OPTIMIZING DRONE DEPLOYMENT
FOR MORE EFFECTIVE MOVEMENT OF GOODS

VICTOR WALKER, INL

Technology Manager: Heather Croteau (in coordination with Nadya Ally)
Energy Efficient Mobility Systems (EEMS)
Vehicle Technologies Office
U.S. Department of Energy

OVERVIEW

Timeline

- Project start date: October 2020
- Project end date: October 2022
- Percent complete: 75%

Budget

- Total project funding: $1150K
  - INL: $900K
  - ANL: $250K

Barriers and Technical Targets

- Little understanding of energy impacts and performance of new technologies
- High risk to develop and deploy advanced vehicles and infrastructure

Partners

- Idaho National Laboratory
- Argonne National Laboratory

Collaboration with Carnegie Melon University

U.S. DEPARTMENT OF ENERGY SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

RELEVANCE

Delivery Drone Deployment Part of Rapidly Developing Shift in Mobility

- Dramatically increasing demand for local, fast delivery
- Quick technology changes that support easier and automated deliveries
- Strong industry and public interest in drones
- Strong opportunity but little understanding of impacts
- Complicated deployment path with many connections
- Need to understand different role of rotary and vertical take-off and landing (VTOL) drones

The Verge
Amazon is still struggling to make drone deliveries work

DroneDJ
Medical drone delivery initiative to transport lab samples in Oregon

TC
Join Extra Crunch
Login
Wingcopter debuts a triple-drop drone to create 'logist

Yahoo Finance
Alphabet's Wing to Begin Biggest U.S. Drone-Delivery Test in Texas

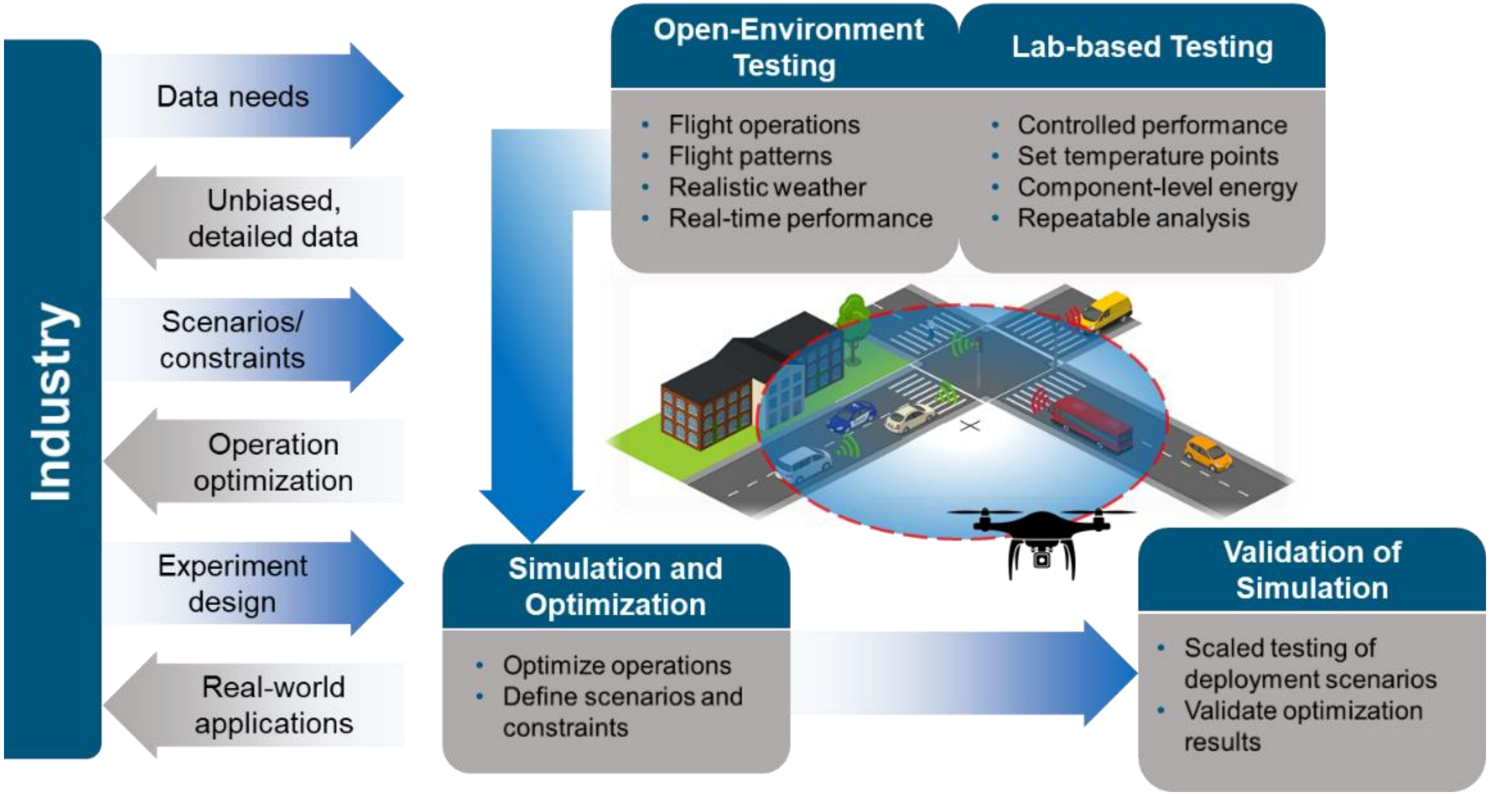
Charged Retail
Why drones won't be taking delivery to new heights…yet -
How many parcels can a drone deliver at a time? One. Two. Maybe three at a push. Meanwhile, a van, car, or even bike can batch delivery.
12 hours ago

ExecutiveGov
FAA Considers Autonomous Drone Delivery Regulations ...

USA TODAY
DEATH & TAXES Filing a last return
STIMULUS PAYMENTS A 4th check?
INVESTMENT CRAZE What's a SPAC?
News Sports Entertainment Life Money Tech Travel Opinion
MONEY
Walmart launches on-demand drone delivery pilot. But it might take time before drones deliver your next order

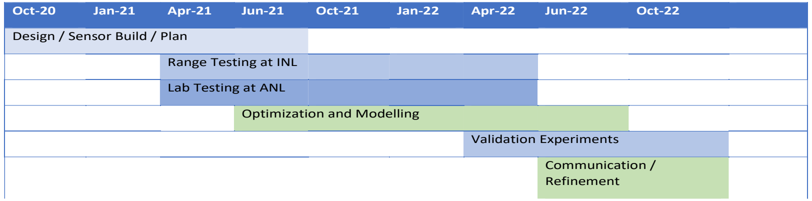
APPROACH

Providing full approach of testing, optimization, and validation



APPROACH

Timing / Milestones



Milestone Name/Description*	End Date*	Status
Develop detailed test plan for drone testing. Design sensors and create data acquisition plan. (Task 1) (INL,ANL)	12/31/2020	Complete
Identify primary scenarios for drone deployment using industry feedback (Task 1). Identify constraints and structure for optimization modelling. (Task 2) (INL)	3/31/2021	Complete
Complete environmental and energy testing of at least one drone in the open-air environment at INL. (Task 1) (INL)	6/30/2021	Complete
Complete energy testing of at least one drone in the controlled lab environment at ANL. (Task 1) (ANL)	6/30/2021	Complete
Complete additional drone testing and perform analysis of initial test data to demonstrate impact of drone operations on energy and throughput. (Task 1) (INL, ANL)	9/30/2021	Complete
Gather data for optimization routines and demonstrate optimization methods on partial data. (Task 2) (INL)	12/31/2021	Complete
Complete system optimization model for drone deployment in two scenarios and compare operation profiles. (Task 2) (INL)	3/31/2022	Complete
Complete a report on component and temperature energy impacts from ANL drone testing. (Task 1. (ANL)	3/31/2022	Complete
Validate the optimization techniques by performing physical delivery experiments in the open-air environment at INL using at least 2 types of drones and 2 scenarios. (Task 3) (INL)	6/30/2022	
Complete the analysis of data and the optimization scenarios. Provide a report of results and complete a draft journal article. (Task 3) (INL)	9/30/2022	

SEVERAL CLASSES OF DRONES

Characterizing a broad range of drones and capabilities

Drone 1 – Large Rotary

- DJI Matrice 600 Pro
- Hexacopter (6 Propellers)
- 21 pounds w/ battery
- Payload up to 13 lbs.
- Max speed 40 mph
- ~10 Mile range
- 5.4 x 5.0 x 2.4 ft

Drone 2 – Small Rotary

- Tarot 650
- Quadcopter (4 Propellers)
- 7.8 pounds w/ battery
- Payload up to 3.3 lbs.
- Max speed 32 mph
- ~2.5 mile range
- 1.7 x 1.7 x 1.1 ft

Drone 3 – Large VTOL

- Wingcopter 198
- 8 propellers – 4 rotating
- ~40 pounds w/ battery
- Payload up to 13 lbs.
- Cruising speed 60 mph
- ~60 Mile range
- 6.5 x 5.0 ft

Drone 4 – Small VTOL

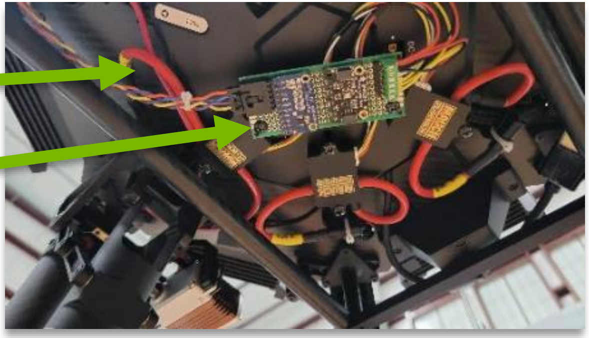
- Wing Drone1
- 12 hover propellers – 2 forward
- ~11.4 pounds w/ battery
- Payload up to 3 lbs.
- Cruising speed 55 mph
- ~12 Mile range
- 4.3 x 3.3 ft

TECHNICAL ACCOMPLISHMENTS : FIELD TESTING

ROTARY DRONE INSTRUMENTATION

Sensors characterize energy consumption, position, & environment

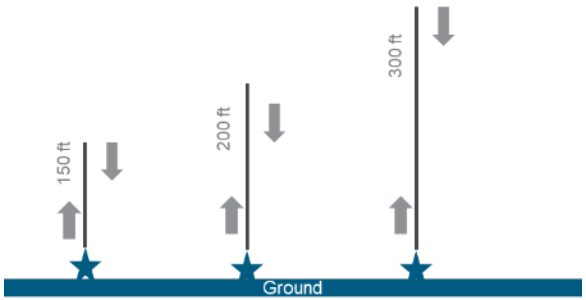
- Full suite of sensors attached to rotary drones during flights
  - 3 Current and voltage sensors
  - Environmental Variables
    - Temperature
    - Pressure
    - Humidity
    - Anemometer (Wind speed and direction)
  - Movement
    - GPS
    - Inertial Measurement Unit
  - Computer system to record sensor reading (approx 5 hz)
  - Extensive development, programming, and testing.



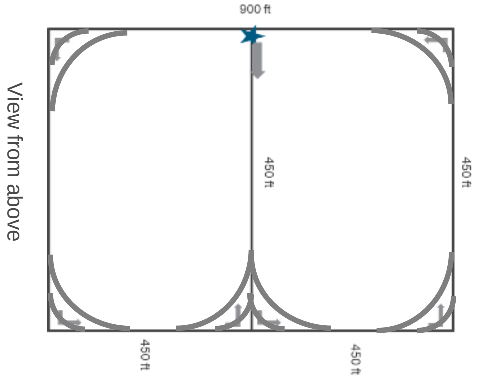
TESTING

Rotary drone tests cover broad range of operations

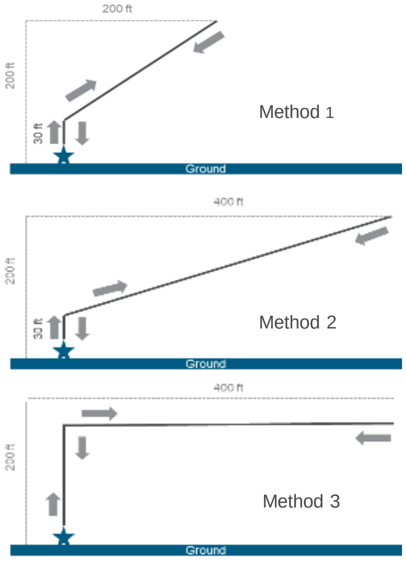
Ascend / Hover / Descend



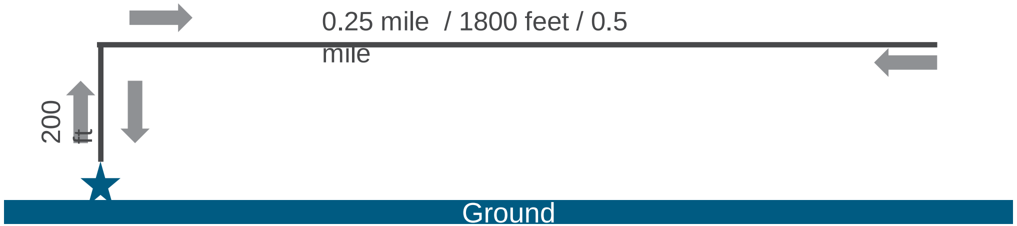
Turning



Angled Ascending



Straight Flight



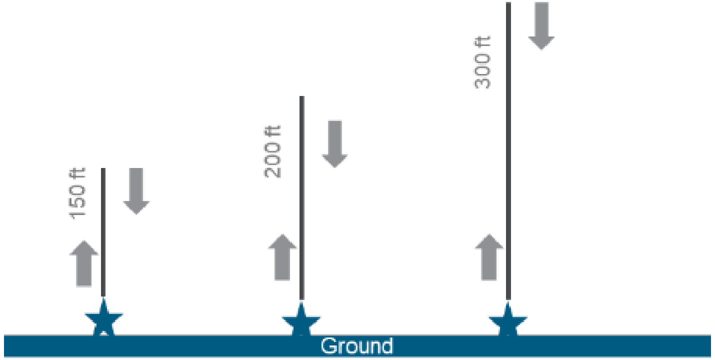
Weights:

- **Large Rotary : 0, 2.5, 5, 10 lb.**
- **Small Rotary: 0, 2.5 lb.**

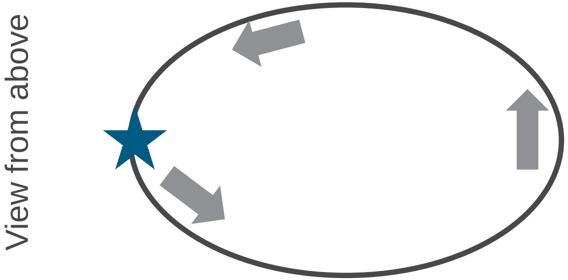
TESTING

VTOL drone tests characterize fundamental operations

Ascend / Hover / Descend



Circuit Flight



200 foot height - 1 mile / 2 mile

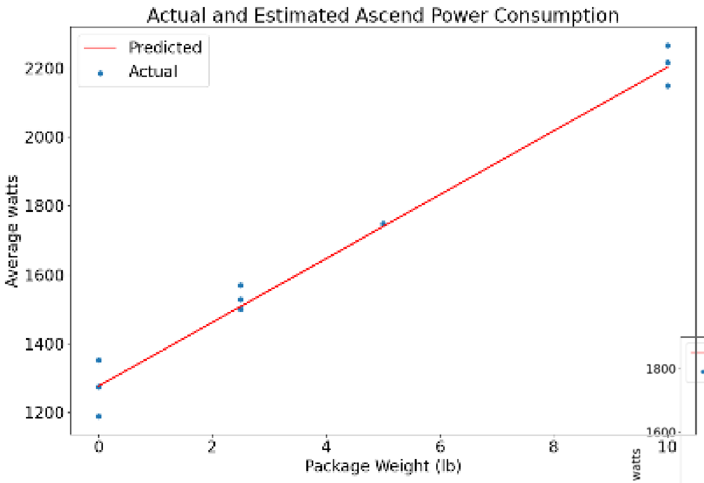
Weights:

- **Large VTOL: 0, 2.5, 5 lb.**
- **Small VTOL Data provided by industry partner rather than tests.**

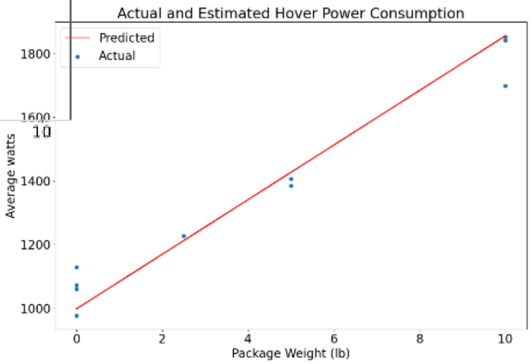
DATA ANALYSIS

Over 200 tests performed and analyzed to provide detailed segments

- Sensor and log file processing
  - Combine log files
  - Divide logs by flights
  - Identify flight Segments
  - Compare energy
- Create models of energy and time from segments.
- Rotary data to be made publicly available



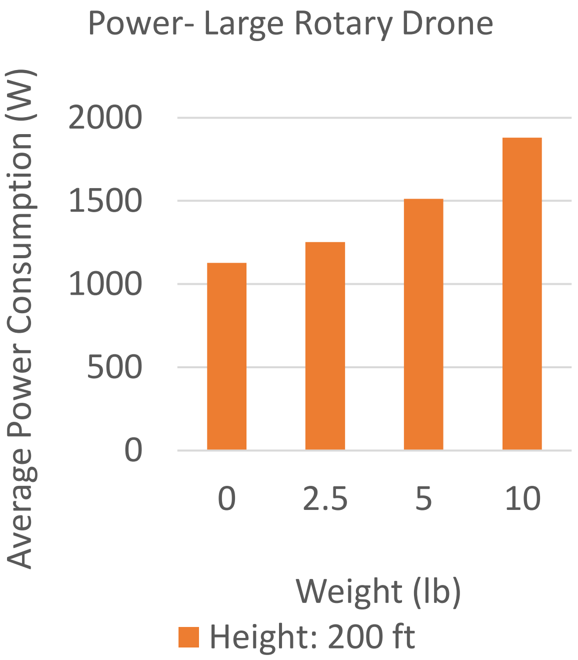
<u>Flight Segments by GPS:</u>
Ascending
Hover
Flight
Descending
Ground

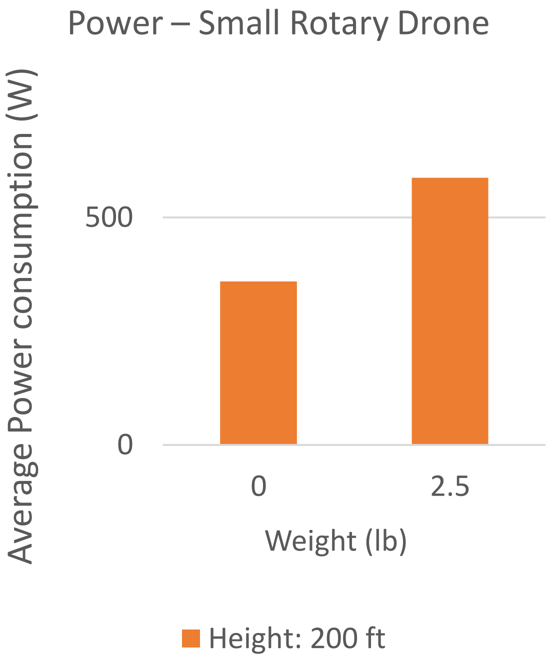


WEIGHT IMPACTS ON POWER USE

Package weight increases energy significantly

- Increase in weight increases power consumption consistently
- Large rotary increase from 0 lb:
  - 2.5 lb : 12-20%
  - 5 lb: 34-40%
  - 10 lb: 67-80%
- Small rotary increase from 0 lb:
  - 2.5 lb : 63-67%

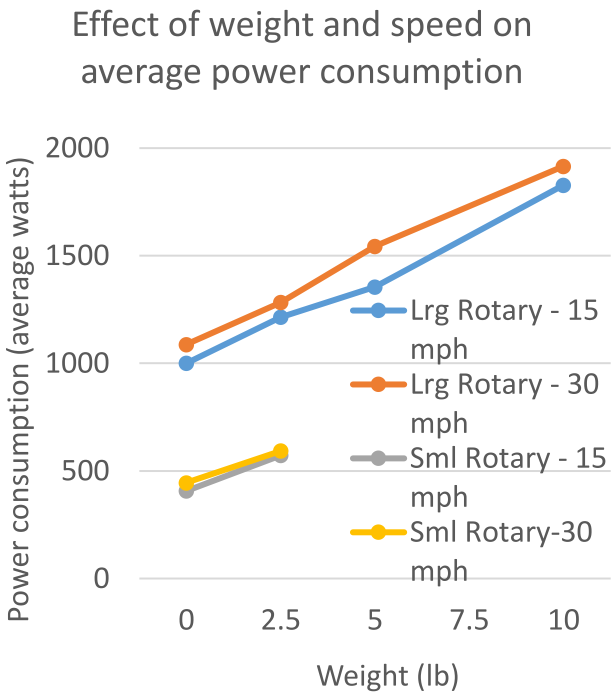


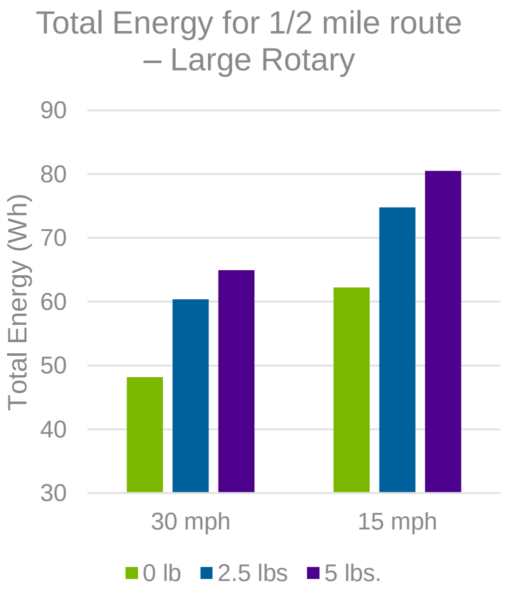


SPEED IMPACTS ON ENERGY

Rotary drone increases power with speed, but decreases total energy

- Faster speeds have slightly higher power use
- Increase in power consumption between 4-12%
- Higher speeds have shorter time in the air and decrease overall energy (~20% decrease on short flight)

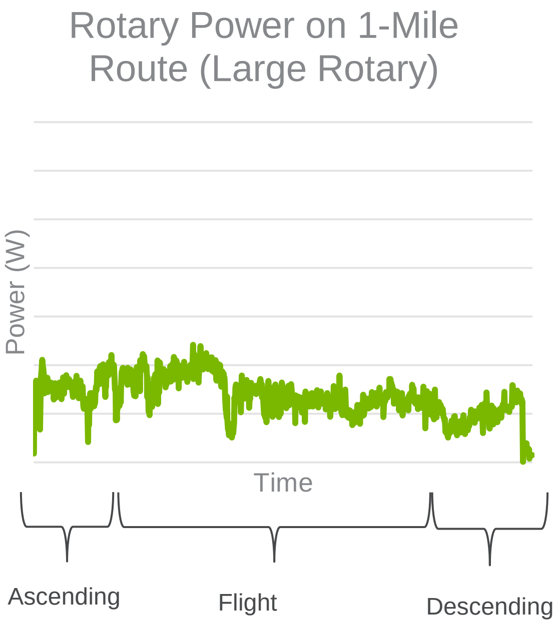




POWER PROFILE

VTOL uses significantly different energy in flight segments

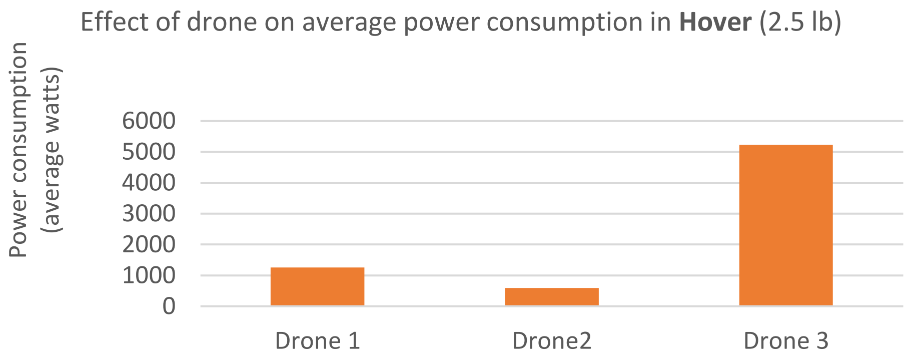
- **Rotary Drones power demand is more consistent across the entire flight**
- **VTOL drones use much less energy during flight mode than in hover or ascending and descending**

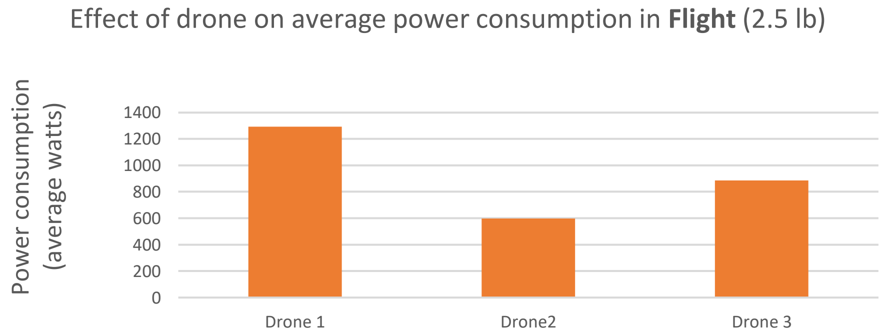


DRONE SIZE IMPACTS ON POWER

Larger drones require more power

- **For the same package weight, lighter drones use much less energy in hover. (Small Rotary 53-55% lower than Large Rotary)**
- **In flight, Large VTOL uses less energy than Large Rotary**



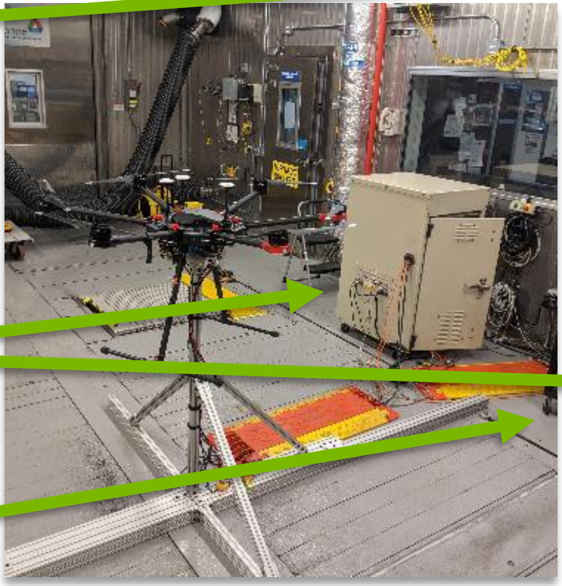


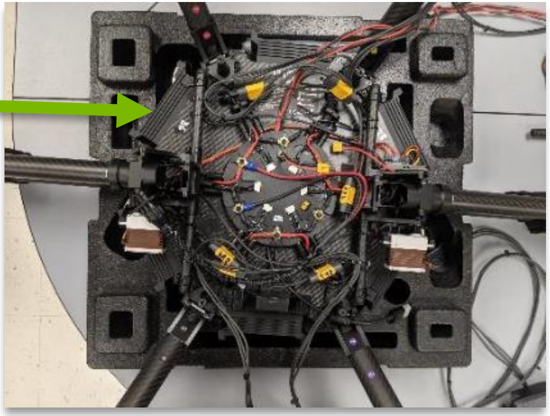
TECHNICAL ACCOMPLISHMENTS : LAB TESTING

LAB TEST INSTRUMENTATION

Obtaining detailed power use information in lab

- **Force Sensor**
  - Nordbo Robotics NRS-6050-D80 sensor for lift force feedback
- **HIOKI Power Analyzer and Current Clamps**
  - **Total battery power output**
  - **Accessories power consumption**
- **Laboratory Environmental Conditions**
  - **Temperature**
  - **Pressure**
  - **Humidity**

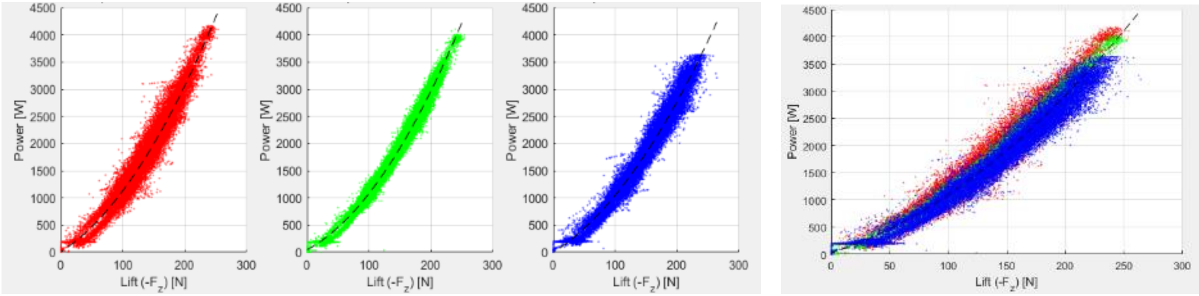




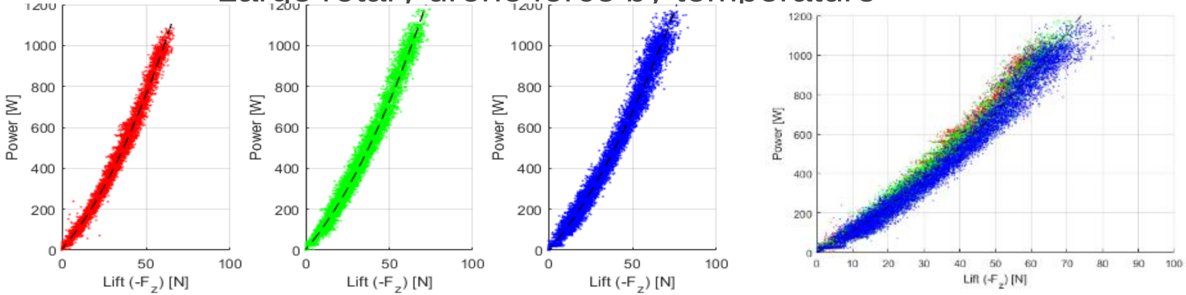
FORCE VERSUS POWER

Testing demonstrates similar force versus power in three temperatures

- **Record force exertion across full motor power**
  - **Tested at 32, 72, 95 degrees F**
- **Both rotary drones Large rotary tested with 2 battery types**
- **Small impact of temperature recorded and analyzed**



Large rotary drone force by temperature

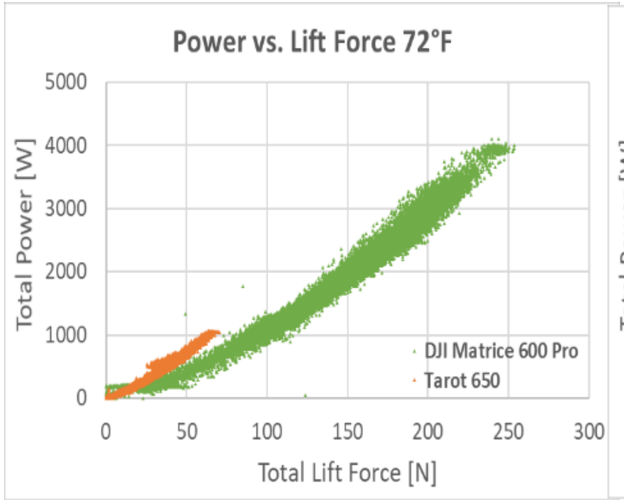


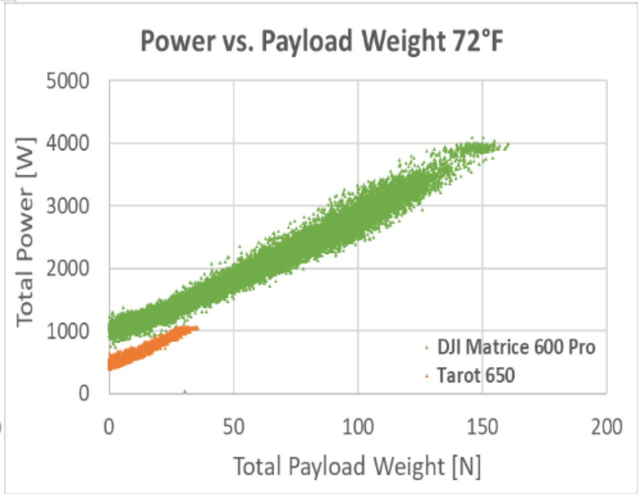
Small rotary drone force by temperature

FORCE LIFT COMPARISON

Large rotary has higher force and efficiency, but more power per payload

- Large rotary drone has significantly higher maximum lift force
- Small rotary drone uses more power for comparable levels of total lift force
- However, small drone uses LESS power per unit of payload weight

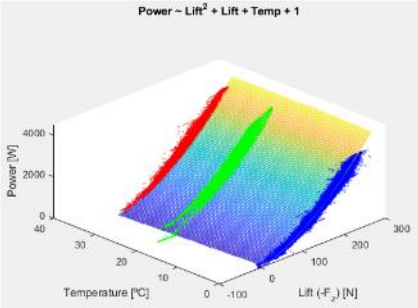


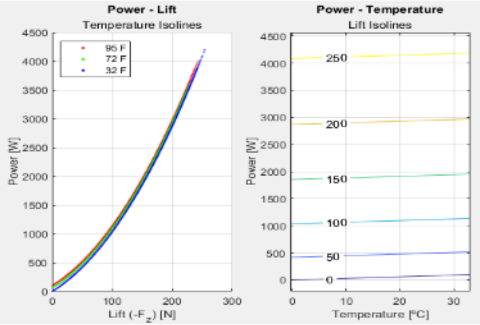


POWER MODEL CREATION

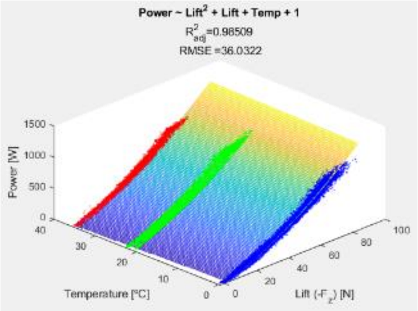
Lift and temperature models indicate slightly more power for higher temps

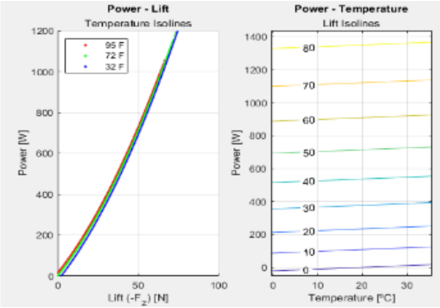
- **Model created to predict power from force**
- **Temperature impact more significant at lower force**
  - **Small rotary ~15% higher at 2.5 lb payload**
  - **Large rotary ~9% higher at 2.5 lb payload**





Drone 1: $P = 0.03845\, L^2 + 6.8514\, L + 3.9673\, T - 54.478$ $RMSE = 153$





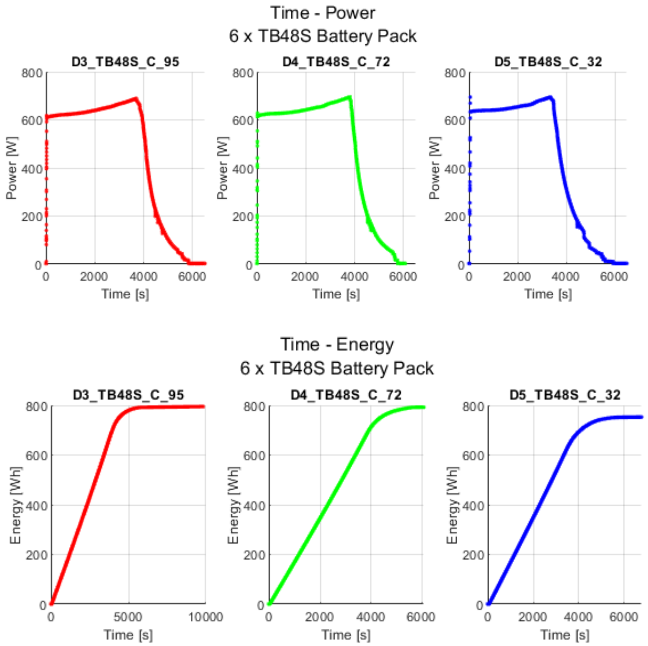
Drone2: $P = 0.0865\, L^2 + 9.9565\, L + 1.0746\, T - 22.429$ $RMSE = 36$

CHARGING CHARACTERIZATION

Testing enables a model of charging times by temperature

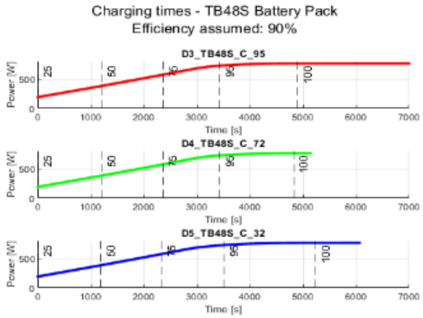
- **Characterization of each system as it charged at 3 temperatures**
  - **2 Battery types for Large Rotary**
- **Model created for predicting time needed to charge to different levels**

Large Rotary Charging



Large Rotary Model

Charge Times [s] – TB48S Battery Pack – Efficiency = 90%			
% SOC Int.	95 F	72 F	32 F
25 – 95	3433 (+0%)	3433	3503 (+2%)
25 – 100	4891(+1.4%)	4824	5238(+8.6%)
50 – 95	2227(-0.22)	2232	2320(+3.9%)
50 – 100	3684(+1.71%)	3622	4055(+11.9%)



TECHNICAL ACCOMPLISHMENTS: OPTIMIZATION

OPTIMIZATION METHODS

Wide-variety of model results analyzed

- Detailed mathematical model created for each scenario
- Demand data from industry partners
- Energy data from testing and partners
- Variables include:
  - Drone Type
  - Energy profile
  - Package weight
  - Speeds
  - Flight profile (Height, routing, times)
  - Delivery window
  - Battery Capacity
  - Battery required
  - Labor Costs
  - Drone/Battery Costs
  - Loading time
  - Battery swap time

Analysis includes:

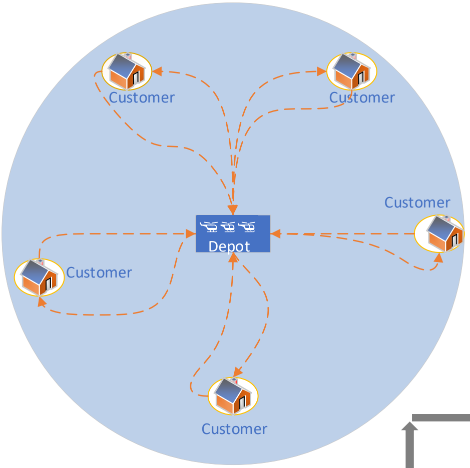
- **# of Drones needed**
- **Routing impacts (such as using road network)**
- **Effect of package weight**
- **# of Battery Swaps**
- **Range/Capacity to delivery**
- **Time needed**
- **Energy by alternatives**
- **Comparison to other vehicles**
- **Mixed fleet options**

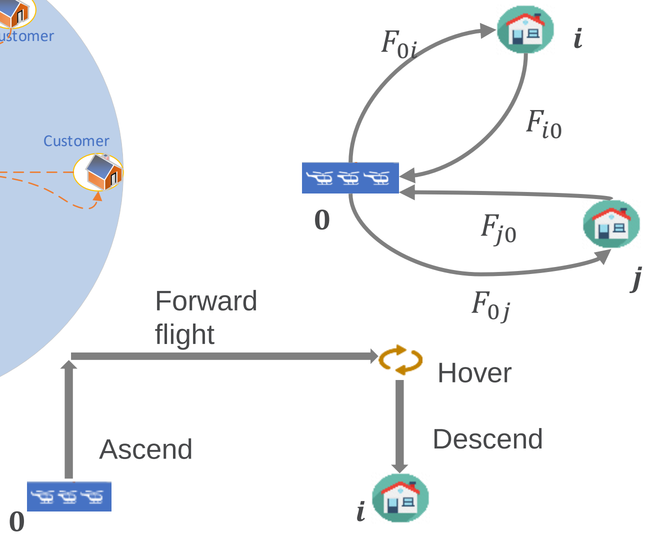
SCENARIOS

Consumer and Business-to-Business models cover large range

- Optimization model developed and run based on real-world demand data
- Scenarios Analyzed:
  - Food Delivery Service
  - Business Courier (With Spright)
- Scenario in Development:
  - Mixed Drone Delivery Service

    (With Wing)





F_{0i} = Ascend energy + Forward flight energy + Hover energy + Descend energy

SCENARIO 1

Direct to consumer deliveries scenario enables impact studies

- **More than 30 insights analyzed so far**
- Delivery from restaurant directly to consumers based on orders
- Based on dense delivery service data (1 hour, 126 deliveries)
- Compares rotary drones performing deliveries
- Used to analyze comparison parameters

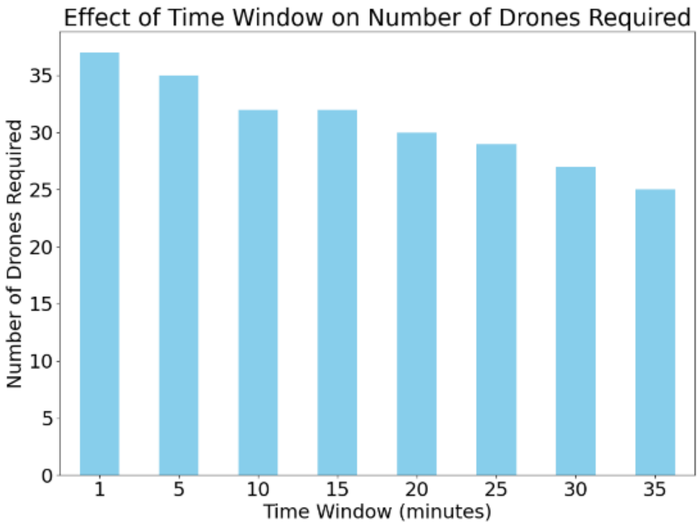
Parameter	Value
Drone speed (mph)	15, 30
Delivery method	Landing, package dropping
Flight Path	Straight, Over road networks
Minimum required battery energy (watt-hour)	60 (10%), 90 (15%), 120 (20%), 150 (25%)
Package weight (lb)	2.5, 5.0, 10.0 (same for all deliveries)
Hovering duration in package dropping (seconds)	30, 60, 90, 120
Time window (minutes)	1, 5, 10, 15, 20, 25, 30, 35
Number of deliveries to make (in one hour)	126, 124, 81

SCENARIO 1 INSIGHT

Large number of drones needed for full-service offering

More responsive delivery windows require significant number of drones

(Based on large rotary drone deliveries)



Percentage reduction in the number of drones required

Time Window	% Reduction
5 minutes	5.4
10 minutes	13.51
15 minutes	13.51
20 minutes	18.92
25 minutes	21.62
30 minutes	27.02
35 minutes	32.43

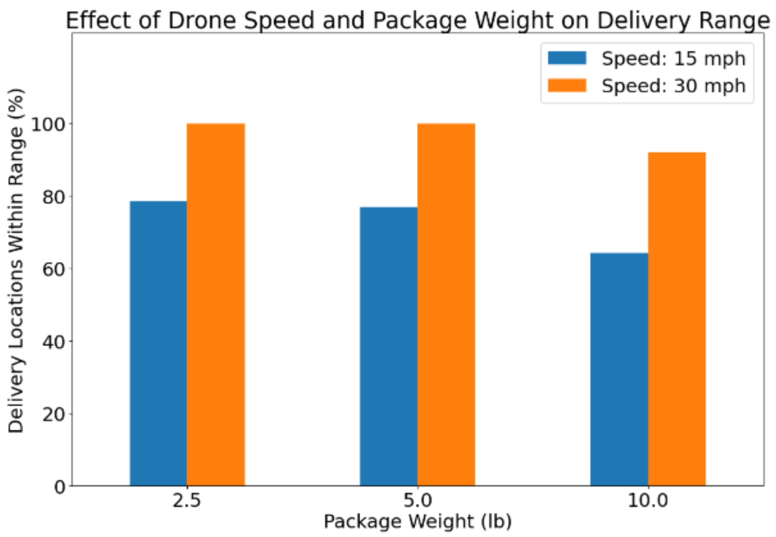
- Speed: 30 mph
- Package weight: 2.5 lb
- Number of deliveries: 126

SCENARIO 1 INSIGHT

Operations impacts availability to offer service

Several routes unavailable based on speed or weight

(Based on sample data of 126 deliveries using large rotary drone)



Number of delivery locations out of range

Drone Speed (mph)	Package Weight (lb)		
	2.5	5	10
30	0	0	10
15	27	29	45

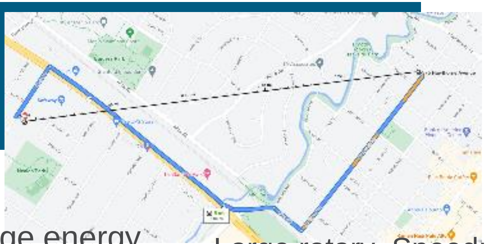
- Delivery method: landing
- Initial battery energy: 600 watt-hour
- Minimum required battery energy: 90 watt-hour

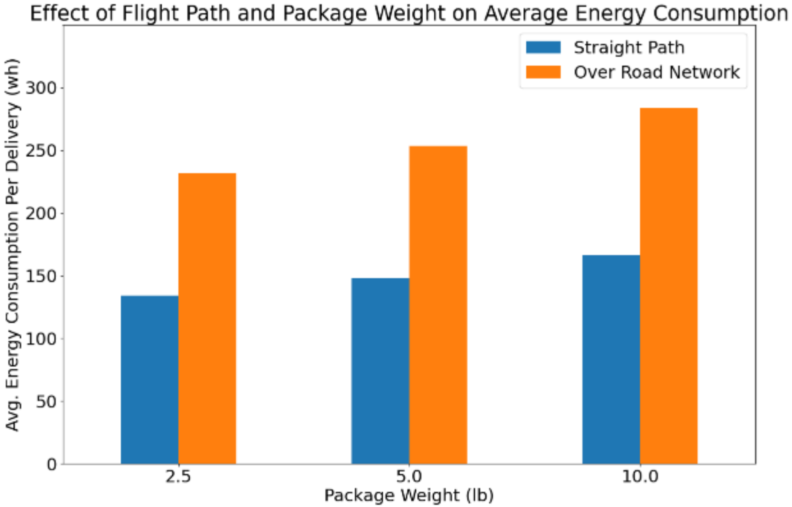
SCENARIO 1 INSIGHT

Following road networks increases energy dramatically

Restrictions to road network eliminates 60% of delivery options

Remaining deliveries have 70% higher energy





Percentage increase in the average energy consumption from straight to over road networks

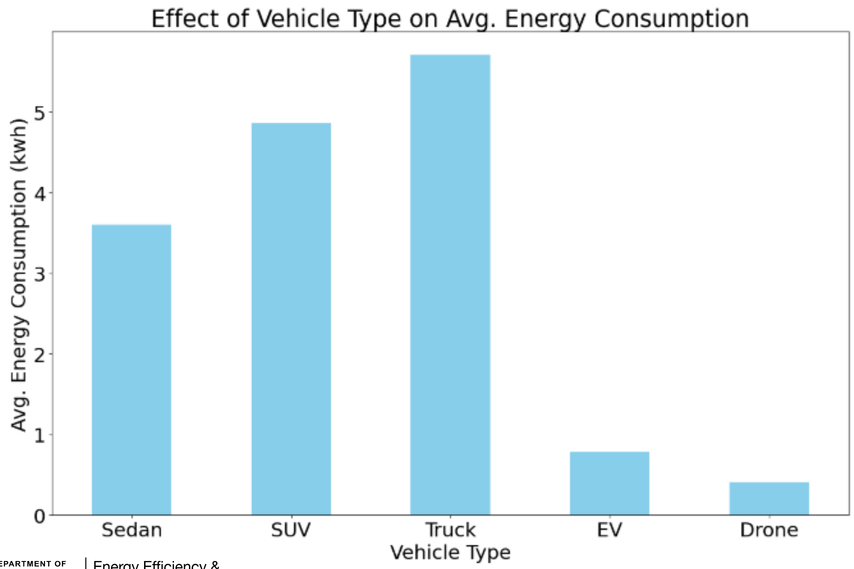
Package Weight (lb)	% Increase in Energy Consumption
2.5	72.22
5	71.25
10	70.54

- Large rotary. Speed: 30 mph
- Number of deliveries: 44 (**excluding 82 out of range**)
- Minimum required battery energy: 90 watt-hour
- Average distance
  - Straight path: 0.93 miles
  - Over road: 1.47 miles

SCENARIO 1 INSIGHT

Drones save energy over traditional vehicles

Even most energy-intensive scenario (15 mph, 10 lbs), drones save energy over vehicles. (Drones offer limited application here due to poor energy scenario)



Percentage increase in average energy consumption compared to using drone

Vehicle Type	% Increase in Energy Consumption
EV	92.16
Sedan	782.35
SUV	1091.18
Truck	1299.51

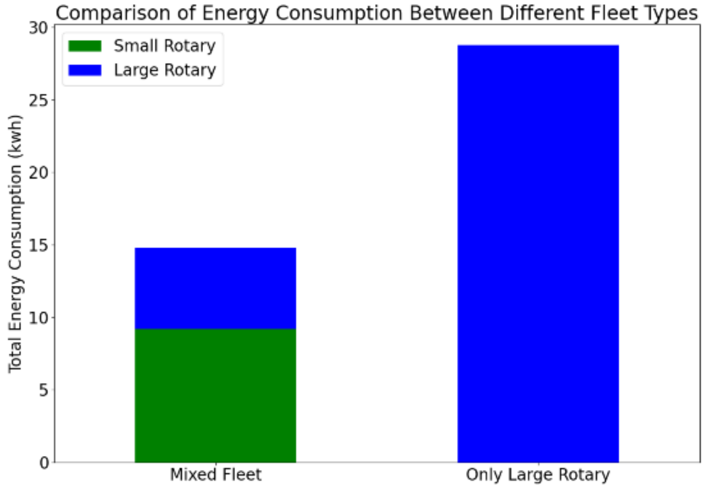
- Large rotary.
- Speed: 15 mph
- Package 10 lb.
- Over Road Network
- Number of deliveries: 44 (excluding 82 out of range)
- Vehicle data from (https://fueleconomy.gov/)

SCENARIO 1 INSIGHT

Mixed fleet of small and large drones can save energy

Small rotary drone has lower energy for smaller packages but has limited range

Mixing drones to serve different deliveries can reduce total energy significantly **(48% reduction)**



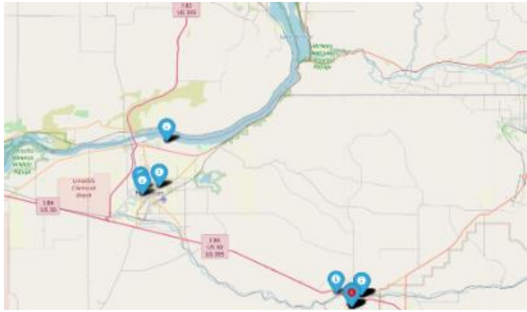
Mixed Fleet: Large and Small Rotary	**Drone Speed (mph)**	
	30	15
Number of locations	126	98
%Energy Reduction	48.52	38.23

- Package 2.5 lbs.
- Straight flight
- Full set of deliveries at 30 mph Reduced to 98 deliveries at 15 mph

SCENARIO 2

Business to Business scenario provides flexibility

- **More than 20 insights analyzed so far**
- Delivery of medical samples from businesses to laboratory
- Based on Interpath lab data in partnership with Spright
  (one week of delivery data)
- Allows charging or battery swap at both ends of delivery and scheduling
- Comparison to courier route
- Two Routes based out of Oregon:
  - Route 1
    - Closer to lab (within 30 miles)
      7 within 5 miles – 4 over 25 miles
    - 11 locations - 81 deliveries
    - 1-3 lbs.
  - Route 2
    - Further from the lab (25- 45 Miles)
    - 12 locations – 52 deliveries
    - 1-8 lbs.

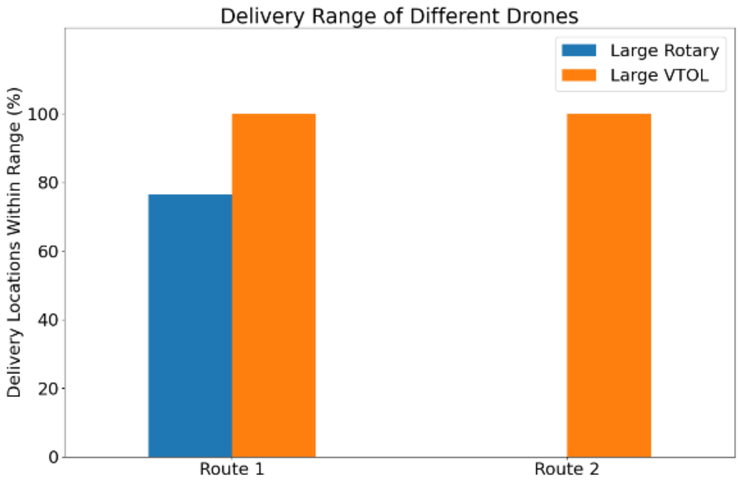


Parameter	DJI Matrice 600 Pro	Fixed-Wing VTOL
Initial battery energy (fully-charged)	600 watt-hour	1450.4 watt-hour
Package loading time	5 minutes	5 minutes
Package unloading time (landing)	30 seconds	30 seconds
Battery replacement time	5 minutes	5 minutes
Flying height	200 feet	200 feet
Hovering duration while returning to depot	5 seconds	5 seconds
Hovering duration while delivering package (landing)	5 seconds	5 seconds
Labor (drone operator) cost	$60/hour	$60/hour
Number of drones operated by an operator	5	5

SCENARIO 2 INSIGHT

Large VTOL drones enable service to rural environments

Large rotary drone and smaller drones (rotary or VTOL) can only service closer locations – even with charging at destination.



Number of deliveries out of range

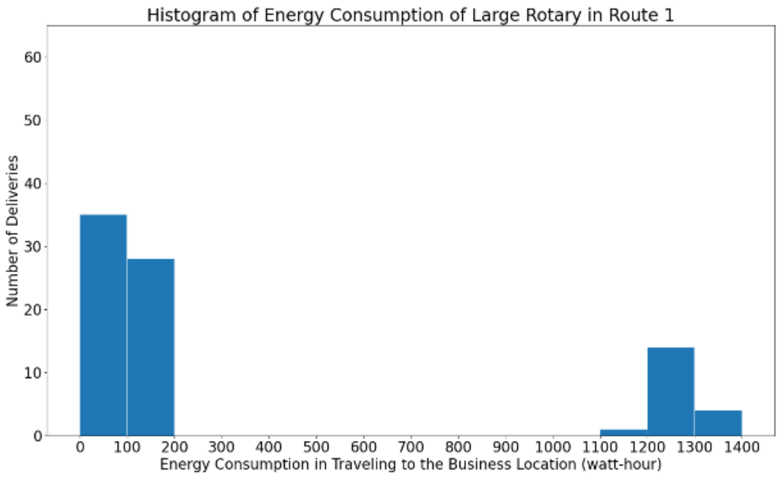
Drone Type	Route 1	Route 2
Large Rotary	19	52
Large VTOL	0	0

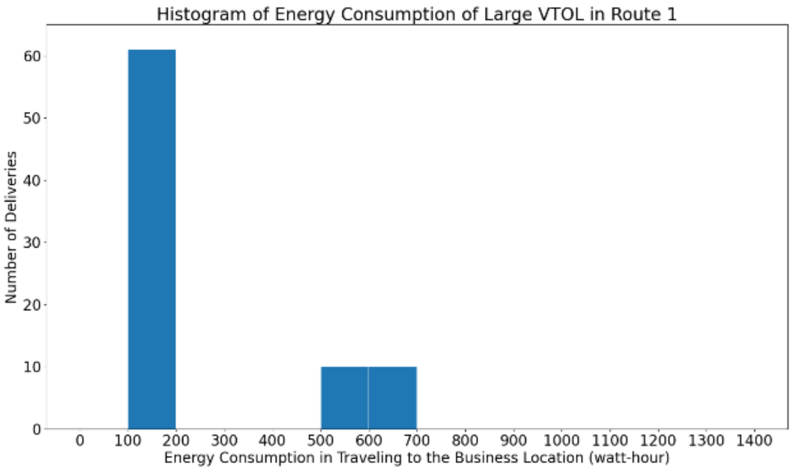
- Drone speed:
  - Large Rotary: 30 mph
  - Large Fixed-wing VTOL: 55 mph
- Minimum required battery energy: 15%

SCENARIO 2 INSIGHT

VTOL drones save significant energy and time over distance

Large rotary drone uses less energy for some short distances, but large VTOL uses significantly less over longer distances (Assuming the rotary drone could finish flight or charge during flight)



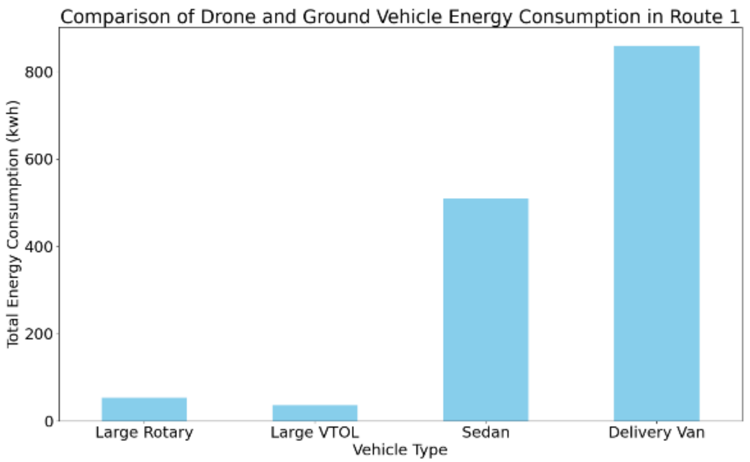


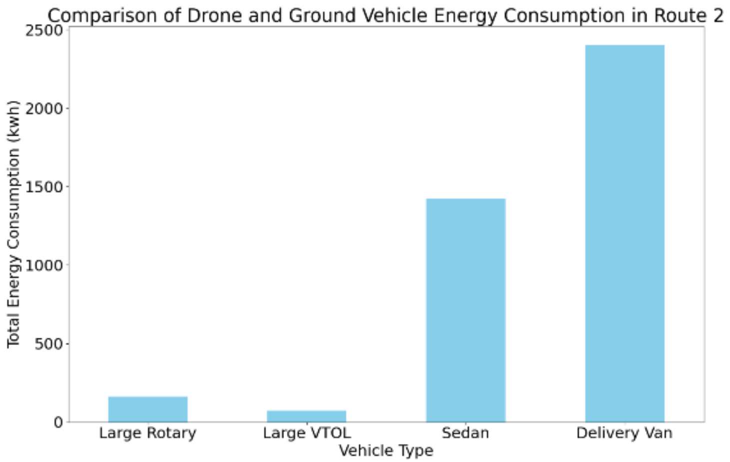
- *Assuming rotary drone could allow additional charging during route

SCENARIO 2 INSIGHT

VTOL drones use less energy than a vehicle route

Even comparted to a vehicle on a delivery route (visiting multiple locations) the drones save significant energy





- Drones visit just one location per trip
- Vehicles visit multiple location in a route.

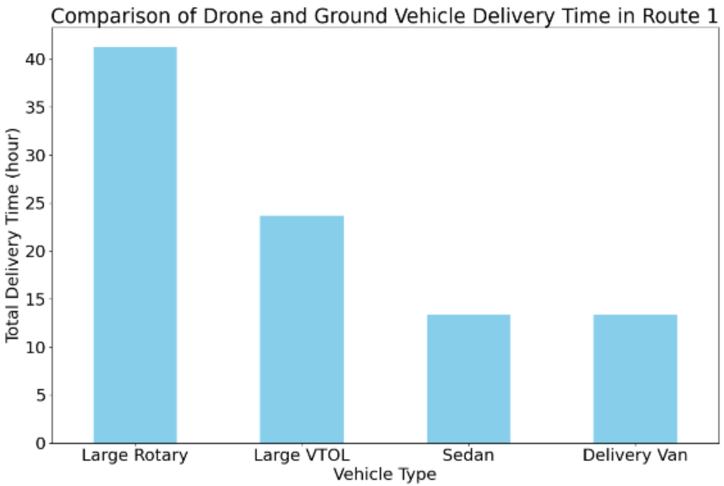
*Assuming rotary drone could charge to complete routes

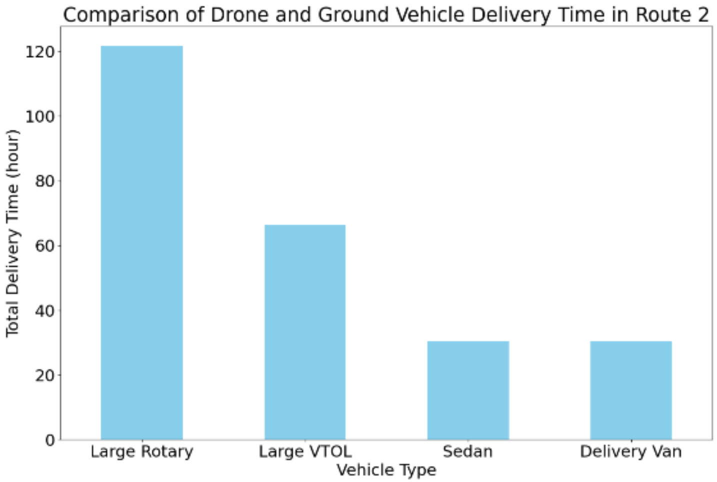
SCENARIO 2 INSIGHT

Vehicles on routes use less total time than drones due to circuits

Routes would require multiple drones to meet current delivery times

Total time for trips of all drones would be higher than single routed vehicle on a circuit





- Drones visit just one location per trip
- Vehicles visit multiple location in a route.

*Assuming rotary drone could complete routes without charging time (not possible)

REMAINING / FUTURE WORK

Modeling, Validation, Communication

Continued scope ongoing:

- **Complete VTOL data comparisons**
- **Complete integration of models**
- **Complete scenario 3 analysis (Delivery as a service)**
- **Complete validation experiment**
  - **Open-air test at INL facilities and others**
  - **Multiple drones / scenarios.**
- **Work with industry partners to apply findings**
- **Publications and Software Disclosure under-way**

- Challenges:
  - Obtaining/processing relevant data
  - Testing with applicable drone types
  - Environmental factors
  - Utilizing and standardizing metrics for comparisons
  - Working within industry needs and confidentiality
  - Hardware and sensor issues

COLLABORATIONS

- **Work with:**
  - **Industry**
  - **Manufacturers**
  - **Service providers**
  - **Users**
  - **Academia**
  - **Researchers**

Primary partners:

- Wing (NDA in place)
- Spright
- Interpath
- Wingcopter
- Carnegie Mellon University

Other Supporting Collaborations:

- Workhorse
- UPS
- Virginia Tech
- FAA
- Vertical Technologies
- UAV Systems Technologies
- Researchers

RESPONSE TO REVIEWERS

- **Focus on industry and collaborations**
- **Identify Metrics**
- **Complexity of systems and metrics**

Suggestion to ensure industry participation and focus:

- Continued focus on ensuring that all model data was provided by true industry partners from real-world data
- A focus on relevant vehicles and real-world applications meant data collection through partners and a shift in scenarios.

Suggestion to create metrics:

- Publications will focus on metrics – but multiple parts are needed due to different energy by flight segments.

Complexity of variable environment conditions

- We are still analyzing the open-air scenarios for environmental impacts, but current models have been useful without incorporating all variables. These may be less significant than thought.
- We continue work to integrate lab and open-air test results into single model.

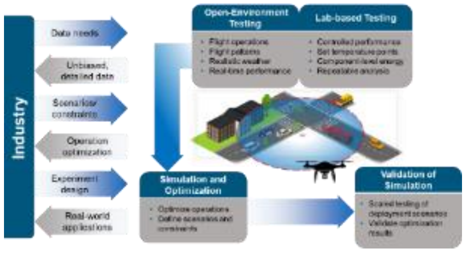
SUMMARY

Critical Data for a Quickly Developing Field

- **Key focus on the needs of a growing industry**
- **Detailed testing to inform critical models**
- **Optimization to help inform industry**
- **Critical validation and communication**

Some key insights:

- Drones offer new and valuable capabilities
  - Possible to enable rural connections
- Use the right drone for the intended business model
  - “Right-sizing” drone can cut energy in half
- Used in the right ways drones can lower time and energy use
  - Mixed fleets can lower overall energy
  - Drones use less energy than vehicles, but it is still significant and needs managing
- Models and tools can provide important insights for drone operations



U.S. DEPARTMENT OF ENERGY
SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

MOBILITY FOR OPPORTUNITY

FOR MORE INFORMATION

Victor Walker
Principle Investigator
Advanced Vehicles
Idaho National Laboratory
victor.walker@inl.gov

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Argonne NATIONAL LABORATORY

BERKELEY LAB

INL Idaho National Laboratory

NREL NATIONAL RENEWABLE ENERGY LABORATORY

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY

TECHNICAL BACKUP SLIDES

MATHEMATICAL OPTIMIZATION MODEL – SCENARIO 1

$$\min \quad C_E \left(\sum_{i\in\mathcal{I}'} \sum_{j\in\mathcal{I}'} c_{ij} z_{ij}\right) + \left(C_d + \frac{C^L}{n_d} + C_d^M\right) \sum_{j\in\mathcal{I}'} z_{0j} + C_{bat}\left(\sum_{i\in\mathcal{I}} y_i\right) \quad (1)$$

- Objective function (1):
  - Component 1: computes total energy cost
  - Component 2: computes total drone cost
  - Component 3: computes total battery cost

s.t.

$$\sum_{i\in\mathcal{I}'} z_{ij} = 1 \qquad \forall j \in \mathcal{I} \quad (2)$$

$$\sum_{j\in\mathcal{I}'} z_{ij} = 1 \qquad \forall i \in \mathcal{I} \quad (3)$$

$$\sum_{i\in\mathcal{I}'} z_{ij} = \sum_{i\in\mathcal{I}'} z_{ji} \qquad \forall j \in \mathcal{I} \quad (4)$$

$$\sum_{j\in\mathcal{I}} z_{0j} = \sum_{j\in\mathcal{I}} z_{jD} \quad (5)$$

$$f_j \geq f_i + (t_u + t_{i0} + t_\ell + t_{0i}) + t_{bat} y_i - M(1 - z_{ij}) \qquad \forall i,j \in \mathcal{I}', i \neq j \quad (6)$$

$$e_i^t \leq f_i \leq \ell_i^t \qquad \forall i \in \mathcal{I} \quad (7)$$

Ensure package is delivered to each location once by a single drone

Packages are picked-up within the specified time window

MATHEMATICAL MODEL (CONT.)

$$g'_j \le ch^0 - (F_{0j} + F_{j0}) + M(1 - z_{0j}) \qquad \forall j \in \mathcal{I}' \tag{8}$$

$$g'_j \le g_i - (F_{0j} + F_{j0}) + M(1 - z_{ij}) \qquad \forall i, j \in \mathcal{I}', i \neq j \tag{9}$$

Compute remaining energy in drone battery after delivering each package

$$g'_j - ch^{min} \ge M_\ell y_i + M(z_{ij} - 1) \quad \forall i \in \mathcal{I}', j \in \mathcal{I}' \setminus \{0\}, i \neq j \tag{10}$$

$$g'_j - ch^{min} \le M_u(1 - y_i) + M(1 - z_{ij}) \quad \forall i \in \mathcal{I}', j \in \mathcal{I}' \setminus \{0\}, i \neq j \tag{11}$$

Determine whether battery needs to be replaced based on the remaining energy

$$g_j \le ch^0 - (F_{0j} + F_{j0}) + Q_u(1 - y_i) + M(1 - z_{ij}) \quad \forall i, j \in \mathcal{I}', i \neq j \tag{12}$$

$$g_j \le g_i - (F_{0j} + F_{j0}) + Q_u y_i + M(1 - z_{ij}) \quad \forall i \in \mathcal{I}' \setminus \{0\}, j \in \mathcal{I}', i \neq j \tag{13}$$

$$g_j \le ch^0 - (F_{0j} + F_{j0}) + Q_u y_0 + M(1 - z_{0j}) \quad \forall j \in \mathcal{I}' \tag{14}$$

Update the battery energy based on whether battery is replaced with a fully-charged one or not

$$z_{ij} \in \{0, 1\} \qquad \forall i, j \in \mathcal{I}', i \neq j \tag{15}$$

$$y_i \in \{0, 1\} \qquad \forall i \in \mathcal{I}, i \neq j \tag{16}$$

$$g_i \ge 0 \qquad \forall i \in \mathcal{I}' \tag{17}$$

$$g'_i \ge 0 \qquad \forall i \in \mathcal{I}' \tag{18}$$

$$f_i \ge 0 \qquad \forall i \in \mathcal{I}' \tag{19}$$